Synthetic fibres and steel fibres in concrete with regard to bond strength and toughness

Alan E Richardson and Sean Landless**

ABSTRACT

"The ability of fibre reinforced concrete composites to absorb energy has long been recognised as one of the most important benefits of the incorporation of fibres into plain concrete" (Golpalaratham and Gettu 1995). Steel and synthetic fibres have been used in concrete floor slabs with success in providing crack control. Slab design using synthetic fibres relies heavily upon manufacturers design guidance whereas steel fibres have better developed independent design guides available to assist their correct use (The Concrete Society 2007a). This paper examines the pull out values of both steel and Type 2 synthetic fibres embedded in concrete and equates their dosage when used in beams to provide near equal toughness values, thus providing the designer with a synthetic/steel fibre ratio by mass of fibre addition for equal performance. According to Nataraja, et al (2000), the most common method to measure toughness, is to use the load-deflection curve. One of the most widely used load-deflection tests has been ASTM 1018, which was used herein to evaluate the post crack toughness; by stating toughness as independent indices and residual strengths based upon the deflection at the formation of the first crack in the beam in relation to fixed points of further deflections under load. The ASTM test was chosen as it has been widely used and it is readily understood by many readers. The research demonstrates that near equal post crack toughness can be achieved in concrete beams using steel and synthetic fibres, at different doses.

Keywords: Steel fibres, synthetic fibres, toughness, beam, load deflection curve.

**School of the Built Environment, Northumbria University, Ellison Building, Newcastle upon Tyne NE1 8ST*
Email: alan.richardson@northumbria.ac.uk

INTRODUCTION

This study is a comparative investigation into the bond and toughness effects of Type 2 synthetic fibres and steel fibres using bespoke pull out tests to identify fibre bond strength and then to establish batching quantities by weight for manufacture of beams for testing to ASTM 1018. The test programme provides an in-depth comparative examination of the effects of these fibres on the concrete beams.

Steel fibres are used in many engineering applications to great effect in controlling cracking of the concrete and enhancing toughness. Steel has a natural affinity with concrete as good bond strength can be developed and the coefficient of expansion for steel and concrete are virtually identical. The steel fibres selected for this study were 50mm long by 1 mm diameter with a tensile strength of 1100 MPa with offset ends to enhance the pull out strength.

Macro synthetic fibres have been added to concrete since the mid-1980s, (Concrete Society Technical Report 65). However, there is still some debate as to the benefits that they can offer the designer and end user. Manufacturers are making claims for their products that would benefit from independent research to identify and quantify the properties and performance claimed. This view is supported by Technical Report 65 which states, "Much development of the use of Type 2 fibres has been by individual manufacturers, supported by a limited amount of published research. There are an increasing number of applications, and some projects have appeared in the trade and technical literature, although very little of this is peer reviewed".

Synthetic fibres for use in concrete are classified in BS EN 14889-2. They fall into two categories: Type 1 (Monofilament < 0.3 mm diameter); and, Type 2 (Macro Synthetic > 0.3 mm diameter). The fibres as used in this study have the following properties: dimensions of 40 mm x 1.67 mm x 0.095 mm, modulus of elasticity of 9.5GPa, a tensile strength of 620MPa, and they are composed of 90% polypropylene and 10% polyethylene.

According to Kiss (2008), it is likely that the market would be more relaxed about expanding its usage [of fibres in concrete], if independent guidance were available to cover aspects such as design, construction and performance in service. This work goes some way in achieving this goal.

METHODOLOGY

According to Bentur and Mindness (2007) "No standard tests are available for fibre pull out characteristics". However single fibre pullout was adopted in place of multiple fibre pull out, to reduce the variables of fibre orientation and eccentric loading.

The test was to be carried out in two parts, the first being fibre pull out tests to establish the bond strength of each fibre, the second part was a three point loading test to establish flexural strength and toughness using beams of each fibre type.

According to Golpalaratham and Gettu (1995), the flexural test is most popular because it simulates more realistically the conditions in many practical situations and the research follows this guidance.

Three test cubes, of two fibre types (6 cubes in total) were formed with six fibres embedded to half of their length and cured for 28 days prior to pull out testing to establish bond strength (See Figures 1 and 2). Single fibres were loaded until pull out failure occurred and the final pull out force was recorded. The procedure was to add weight by 0.1kg for synthetic samples and 1.0 kg for steel samples, at 60 second intervals, until pull-out failure occurred. Creep was noticed with some of the synthetic fibres and no further load was added at this point. Failure occurred usually within two minutes from this point.

Using the pull out data, the steel and synthetic fibre bond strength performance was examined to establish relative fibre dosage per beam type.

Golpalaratham and Gettu (1995) state, "most standards are comparable, as ACI 544 uses a ratio of

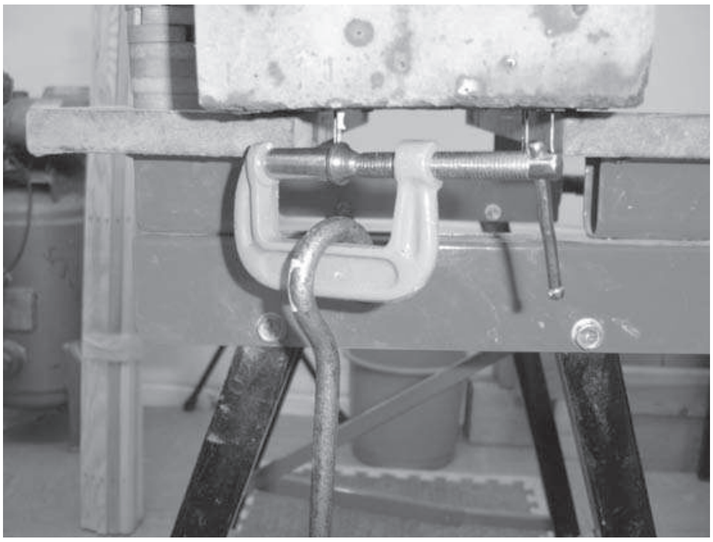

Figure 1 – G clamp providing a plane clamp for fibre pull out

Figure 2 – Steel fibre under pull out load

load/deflection curve so does ASTM 1018, which is essentially the same, however the limiting deflection analysis in ASTM 1018 was considered a most useful quality for a paired comparison test.

Six 100 x 100 x 500 mm beams were cast with each fibre type (12 in total) and they were tested to ASTM C1018 to provide flexural strength, first crack load and toughness data, using a three point loading configuration as shown in Figure 3.

Stahli and Mier (2007) comment that the fibres tend to align along the walls of the moulds and it can be shown that these highly reinforced surface layers add significantly to the strength of the beam". This effect of fibre orientation applies equally to both beams, although synthetic fibres will be greatly affected by the concrete viscosity and aggregate size.

Whole beams were used rather than cut beams because according to Stahli and Mier (2007), "no significant difference was observed in the fracture process between moulded and cut specimens and given fibres when cast, tend to align along the walls of the mould, this quality was sought to produce the most representative test conditions of concrete when cast against formwork.

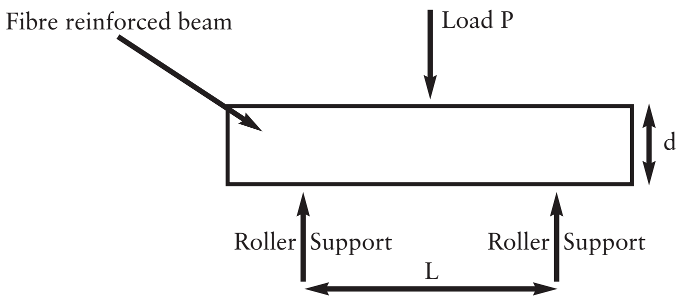

Figure 3 – Beam loading arrangement

Formula for flexural strength

$$R = \frac{3Pa}{bd^2} \quad \text{(from ASTM C78)}$$

P= applied load, a= distance between line of fracture and nearest support,

b= average width of beam, d= average depth of beam, L = span length

In accordance with ASTM C 1018, the toughness indices (I) and residual strength values (R) are calculated as follows:

- Determine the first-crack deflection as the deflection corresponding to the length OB in Figure 3. Determine the area under the load-deflection curve up to the first-crack deflection, i.e. the triangular area OAB.
- Determine the area under the load-deflection curve up to a deflection of 3.0 times the first-crack deflection. This corresponds to the area OACD where OD equals 3.0 times the first-crack deflection. Divide this area by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_5.

- Determine the area under the load-deflection curve up to a deflection of 5.5 times the first-crack deflection (area OAEF). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{10}.
- When required, determine the area under the load deflection curve up to a deflection of 10.5 times the first-crack deflection (area OAGH). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{20}.
- Determine the residual strength factor $R_{5,10}$ as $20(I_{10} - I_5)$, and, when required, the residual strength factor $R_{10,20}$ as $10(I_{20} - I_{10})$.

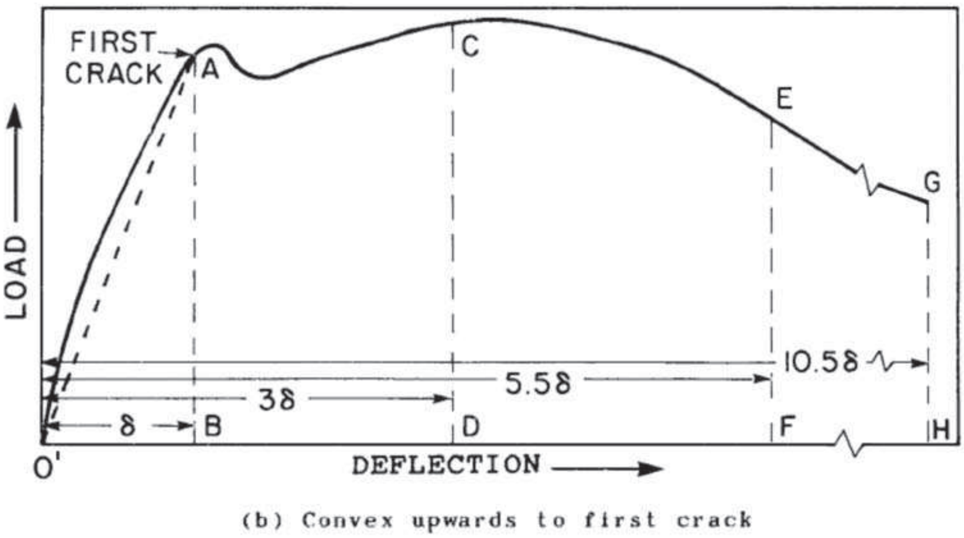

Figure 3: Determination of toughness indices. (Source ASTM 1018 - 1997)

ASTM C1018 evaluates the flexural performance of toughness parameters derived from fibre-reinforced concrete, in terms of area under the load-deflection curve. This is obtained by testing a simply supported beam under third-point loading. The toughness determined in terms of area under the load-deflection curve is an indication of the energy absorption capability of the particular test specimen. Ultra-sonic transducers were held at opposite ends of the specimen to allow direct transmission of ultra-sonic pulses through the specimen. This was done to allow greater accuracy in the determination of the first crack load values.

Bentur and Mindness (2007) comment that, "as cracking occurs almost immediately after loading begins, it is difficult to define this point (first crack) unambiguously". The use of a ultra sonic testing apparatus (PUNDIT) was used to assist in identifying the first crack clearly by monitoring the pulse velocity. This method was very sensitive to identifying minor cracks within the beam cross section.

MATERIALS

BS-EN14889 -2 covers synthetic fibres and their manufacture, and divides polymer fibres into two main classes according to their physical form (Table 1), and Type 2 fibres are generally used 'when an increase in residual strength is required'.

Class 1a	Micro fibres < 0.30mm diameter, mono-filament
Class 1b	Micro fibres > 0.30mm diameter, fibrillated
Class 2	Macro Fibres > 0.30mm diameter

Table 1 – BS-EN 14889 Polymer Fibre Classification

The tensile strength of macro synthetic fibres varies according to manufacturer; manufacture method, and the polymers used in their manufacture. Most suppliers quote the tensile strength of their fibres in their respective literature; most fibres on the market today range from 100-650 Mpa (Concrete Society 2007a).

The density of polymeric fibres is of the order of 900 kg/m^3, and, generally, is slightly less than that of water. Typical dosages vary up to a maximum of about 12 kg/m^3 which is equivalent of approximately 1.35% by volume (Concrete Society 2007a).

The size of the synthetic fibre used was 40 mm x 1.67 mm x 0.095 mm composed of 90% polypropylene and 10% polyethylene.

Steel fibres have been in use in the construction of concrete slabs since the 1970's, and their commercial use in Europe, the USA, and Japan has been gathering momentum ever since (Concrete Society 2007) Their

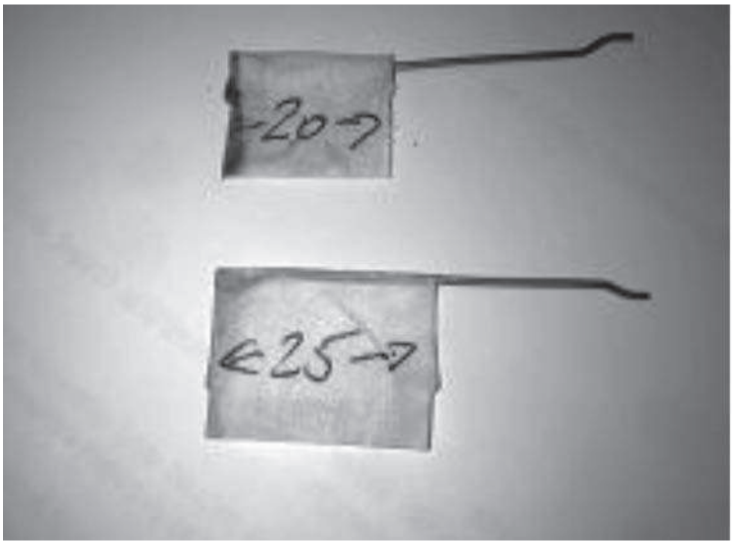

Figure 4: – Steel fibre with depth marker

main applications have been in ground supported floors, pile supported floors, paved areas, sprayed concrete, composite slabs and pre-cast concrete elements.

BS EN14889-1 classifies steel fibres into five groups, according to their method of manufacture: 1 cold drawn wire, 2 cut sheet, 3 melt extract, 4 shaved cold drawn wire, and 5 milled from blocks.

Steel fibres come in a variety of sizes and shapes. The ratio of length to diameter (aspect ratio) can vary from 20:1 to 100:1, with a maximum length of about 60mm. To gain maximum performance from pull out tests, steel fibres come with enlarged, flattened or hooked ends, and usually have roughened surface textures or crimped profiles to provide additional bond strength.

The cold drawn fibre as used (Figure 4) was 50mm long by 1 mm diameter with a tensile strength of 1100 MPa and has a nominal aspect ratio of 50:1 The hooked ending shape added extra adhesion between the fibre and the concrete leading to increased pull out strengths.

The concrete mix design (C50) was used to reflect the potential use of fibre concrete in a structural situation and the component parts per m^3 were 400 kg of CEM 11, 700 kg of coarse sand, 1020 kg of 20 mm gap graded gravel with an optimum water cement ratio of 0.5 and variable fibre dosage. C50 was specified for plain concrete and no consideration in strength reduction was taken for the fibre additions (Richardson 2006).

RESULTS

A compressive strength test was carried out on six 150mm x 150mm x 150mm plain pull out cubes, to BS EN 12390-3. The mean value of the compressive strength of the concrete was 53 N/mm^2 and the standard deviation was 4.7. The fibre concrete would have different compressive strength properties due to inclusion of the fibres and this was not measured as what was sought, was the strength of plain concrete. The reason for this was to evaluate the bond strength between fibre and concrete.

Density was determined for the concrete and it was found to be a mean value of 2345kg/m^3. The standard deviation for density was 13 and this shows a consistent series of concrete batches.

Pull out test results are shown in Table 2 and the bond strength was calculated per fibre. It was not possible to embed the fibres precisely at an accurate and repeatable depth so each one was marked with a pen prior to the pull out test commencing and the embedded depth was measured to determine the area in contact with the concrete.

The orientation of the embedded fibre to the normal plane had an influence upon the pull out values as shown in lines 2 and 16 of the steel fibre pull out table (Table2) and line 1 of the synthetic fibre pull out test, which was removed as an outlier. High pull out values ere obtained due to the angle of the fibre when compared to the plane pull out force. Hannant (1998) observed a similar effect where fibres bridged the rupture plane.

The steel fibres bond well to the concrete/cement matrix and therefore have a higher pull out value than synthetic fibres. Establishing this value is important to evaluate the relationship of fibre pull out values which will determine the relationship of fibres added to a concrete mix. This is the essence of this research. To equate similar toughness values between steel and synthetic fibres, a steel fibre concrete mix was chosen using 40 kg/m^3 of steel fibres and synthetic fibres were added at a higher rate due to their lower bond and tensile strength to provide near equal performance.

From the pull-out test results, it was calculated that steel fibres have an increased pull out bond strength when compared to synthetic fibres at a ratio of 1: 8.77.

For an equal weight of fibres there are 51 times more synthetic fibres than steel.

For the purpose of this comparison, a concrete mix containing 40kg of steel fibres per m^3 was selected, being a high commercial fibre dose. To provide an equal number of fibres per m^3, 0.784kg of synthetic fibres were needed. (40/51 = 0.784).

Sample No.	Failure			Area Imbedded (mm^2)	Bond Strength (N/mm^2)
	Mode	Load (kg)	Force (N)		
Synthetic Type 2 fibres					
1	P O	5.7	-	-	-
2	P O	2.2	21.582	54.620	0.395
3	P O	2.5	24.525	52.633	0.466
4	P O	2.4	23.544	62.155	0.379
5	P O	2.4	23.544	63.066	0.373
6	P O	2.6	25.506	57.132	0.446
7	P O	2.3	22.563	55.670	0.405
8	P O	2.2	21.582	55.586	0.388
9	P O	2.7	26.487	51.860	0.501
10	P O	2.2	21.582	54.758	0.394
11	P O	2.9	28.449	57.242	0.497
12	P O	3.3	32.373	55.366	0.584
13	P O	2.7	26.487	48.742	0.543
14	P O	3.7	36.297	55.807	0.650
15	P O	2.7	26.487	56.773	0.466
16	P O	2.5	24.525	49.315	0.497
17	P O	2.9	28.449	51.971	0.547
18	P O	2.5	24.525	55.421	0.443
Average Bond Strength (N/mm^2)					0.470
Steel fibres					
P O	24.6	241.326	78.525	3.072	
P O	49.6	486.576	67.469	7.212	
P O	19.6	192.276	69.625	2.761	
P O	29.6	290.376	62.770	4.626	
P O	29.1	285.471	68.353	4.176	
P O	29.1	285.471	66.087	4.319	
P O	29.6	290.376	78.967	3.677	
P O	23.6	231.516	65.341	3.543	
P O	27.6	270.756	72.057	3.757	
P O	23.6	231.516	73.522	3.149	
P O	27.6	270.756	74.849	3.617	
P O	31.1	305.091	69.652	4.380	
P O	19.6	192.276	66.695	2.883	
P O	35.6	349.236	70.482	4.912	
P O	26.6	260.946	76.729	3.401	
P O	47.1	470.058	73.538	6.392	
P O	25.1	250.498	69.060	3.627	
P O	36.1	360.278	75.363	4.781	
Average Bond Strength (N/mm^2)					4.120

Table 2 Pull-out test results

The number of synthetic fibres was increased by the ratio of the pull out strengths (8.77) to give a balanced fibre addition in terms of bond strength, weight and numbers: (0.784 x 8.77 = 6.88 kg/m^3).

This approach suggests that equal performance can be achieved with 40kg/m^3 of steel fibres or 6.88 kg/m^3 of synthetic fibres; the latter dosage falls within maximum of 7kg/m^3 recommended by the manufacturer (Grace, 2008).

The 12 beams were tested in accordance with ASTM 1018 using a three point loading with roller centres at 300mm and the results are shown on Tables 3 to 6. The toughness indices limits are detailed in Figure 3.

Fibre beam sample	1st Crack Load (kN)	1st Crack Deflection (mm)	Fibres Spanning the Rupture Plane	I_5	I_{10}	I_{20}
1	9.051	0.406	194	3.008	5.723	10.104
2	9.286	0.300	181	2.167	5.169	9.068
3	9.757	0.462	202	3.156	5.460	9.199
4	7.289	0.284	138	3.259	6.180	11.890
5	7.676	0.443	126	3.027	5.616	9.094
6	8.001	0.437	163	3.224	5.987	10.408
Mean	**8.5**	**0.389**		**3.0**	**5.7**	**10.0**

Table 3 – Type 2 fibre beams – Toughness indices and beam properties

The load deflection ratio at first crack is L/771, which is a very slight deflection compared to permitted concrete design deflections.

Steel beam sample	1st Crack Load (kN)	1st Crack Deflection (mm)	Fibres Spanning Rupture Plane	I_5	I_{10}	I_{20}
1	10.92	0.471	42	2.788	4.541	6.940
2	9.554	0.420	33	3.233	5.562	8.659
3	9.480	0.478	31	3.268	6.105	9.854
4	10.4	0.395	37	2.681	4.630	7.277
5	11.28	0.490	26	2.885	4.410	6.546
6	10.426	0.394	36	3.180	5.463	8.419
Mean	**10.68**			**3.0**	**5.1**	**8.0**

Table 4 – Steel fibre beams – Toughness indices and beam properties

From examination of the rupture plane after the test, specimens containing the synthetic fibres had an average of 163 fibres spanning the rupture plane, where specimens containing steel fibres had an average of 34 fibres. This is within 17% of the ratio of fibres added to each batch compared to the design quantities, which suggests a slightly uneven distribution throughout the specimens.

Tables 5 and 6 show flexural strength and residual strength values and these are slightly skewed by the steel beams having a slightly higher flexural strength which automatically reduces the toughness indices and residual strength values due to the area of OAB.

Sample	Flexural Strength (N/mm^2)	Residual Strength $R_{5,10}$	Residual Strength $R_{10,20}$
1	4.07	54.30	43.81
2	4.18	60.04	38.99
3	4.31	46.08	37.39
4	3.28	58.42	57.10
5	3.45	51.78	34.78
6	3.60	55.26	46.21
Mean	**3.8**	**54.3**	**43.1**

Table 5 – Flexural strength and residual strength of synthetic fibre beams

The mean value of I_5 for steel is 3.0 and 3.0 for synthetic fibres which are identical when rounded up to 0.1 as recommended by ASTM 1018.

Synthetic fibres performed slightly better than steel for values of I_{10} and I_{20} where the values were 5.1 and 8.0 for steel and 5.7 and 10.0 for synthetic fibres, as a consequence of these values the residual strength values were proportionally higher for synthetic fibres. Synthetic fibres performed 12% better than steel at I_{10} and 20% better at I_{20}.

Although there is a toughness difference between the beam types, bye and large the results are nearly equal when fibre distribution, compressive and flexural strength variations are taken into account.

Sample	Flexural Strength (N/mm^2)	Residual Strength $R_{5,10}$	Residual Strength $R_{10,20}$
1	4.91	33.04	23.99
2	4.29	46.58	30.97
3	4.27	56.74	37.49
4	4.68	38.98	26.47
5	5.07	30.50	21.30
6	4.69	43.64	29.56
Mean	**4.7**	**41.6**	**28.3**

Table 6 – Flexural strength and residual strength of steel fibre beams

The steel beams have a 24% higher flexural strength than the synthetic fibre beams

Residual strength $R_{5,10}$ for synthetic fibres is 31% greater than the steel value and the residual Strength $R_{10,20}$ for synthetic fibres is 52% greater than the steel value.

The synthetic fibre results were skewed by beam 4 providing and unusually high residual strength and the steel fibre beam 5 was a particularly low value. A larger sample size would reduce the scatter in the measurements.

Figure 5 shows the area under the load and deflection representing toughness of the individual beams and the close post crack performance of each beam. The deflection readings have been plotted to the maximum extent of the largest value of I_{20}.

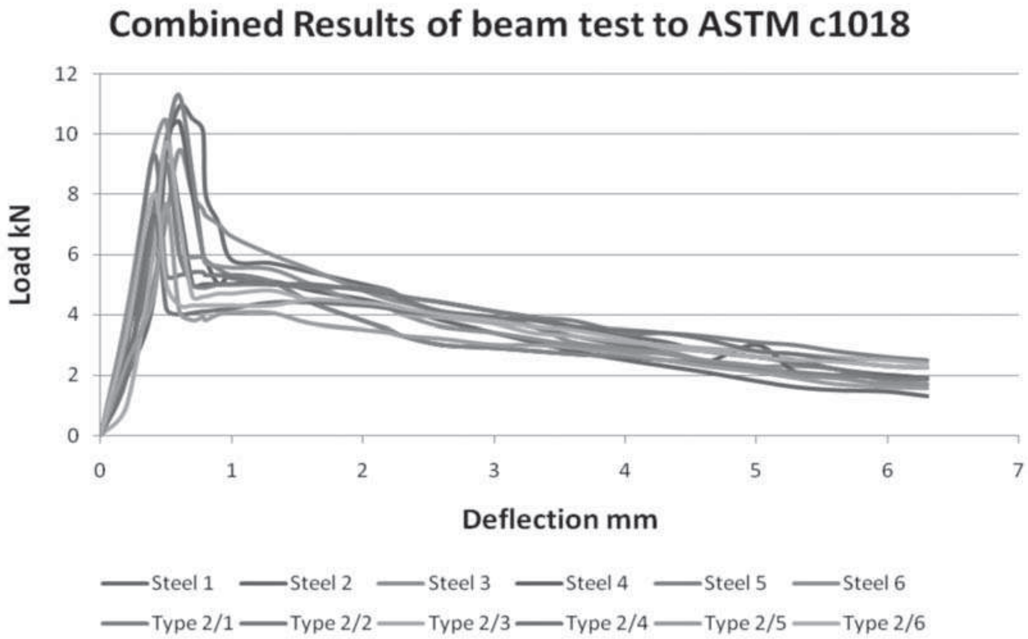

Figure 5 – Combined Results of beam test to ASTM c1018 test using Type 2 synthetic and steel fibre Reinforced Concrete – showing load and deflection

Comparing the performance of steel fibres and high modulus synthetic macro Type 2 fibres in concrete, with regards to toughness and strength, it was found that synthetic Type 2 fibres and steel fibres can perform equally well if the fibre balance is equated accurately. Figure 6 shows the mean performance values of each beam type and whilst the Type 2 synthetic fibres outperform the steel fibres the difference is not significant given the small scale of the investigation. The greater deflection and higher load of the steel fibre beams has reduced the I_5 value to equate with the Type 2 synthetic fibre beam with lower deflection and lower first crack values.

The Type 2 and steel fibre reinforced concrete performed equally well in terms of first crack strength and in the take up of the force after the first crack has formed, as seen in Figure 6, however two steel fibre beams had higher flexural strength values than the other beams within the cohort and with a small population of 6 beams of each type it does skew the results as the area OAB is larger for the steel fibre beams which reduces the toughness indices and residual strengths.

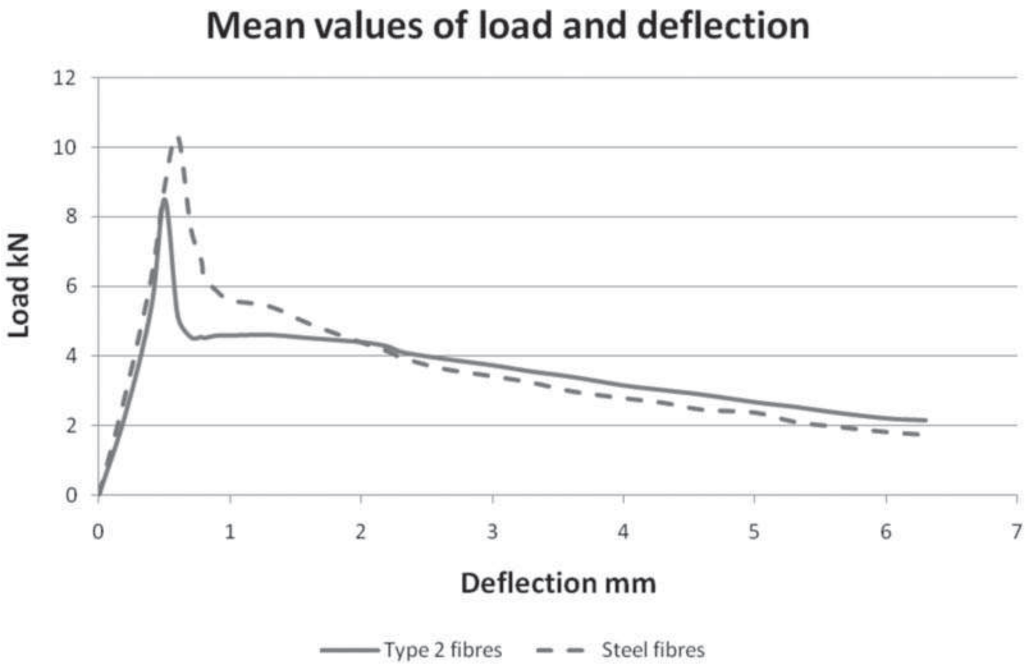

Figure 6 – Mean values of load and deflection

CONCLUSION

This study has shown that a near equal performance can be achieved with suitable dosages of steel and synthetic fibres, allowing the designer to make an informed judgement. A larger sample size would reduce the scatter in the results and further research is required to refine the results. For the purpose of this test a small reduction in Type 2 synthetic fibres may provide equal performance with regards to residual strength and toughness. Further work is required to refine the results. However Lee and Barr (2003) comment that, “test specimens taken from industrially prepared fibre reinforced concrete displayed similar characteristics compared to that observed with test specimens prepared under laboratory conditions, with regards to strength, fracture characteristics and in particular to the variation observed”. This indicates the work detailed herein may be replicated in full scale construction projects with confidence.

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